

DISCRIMINABILITY BETWEEN ALTERNATIVES IN A SWITCHING-KEY CONCURRENT SCHEDULE

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Six pigeons were trained to discriminate between two intensities of white light in a symbolic matching-to-sample procedure. These stimuli were then used to signal which schedule was available on the main key in a switching-key concurrent schedule. The concurrent schedules led to a symbolic matching-to-sample phase in which the subject identified the concurrent schedule to which it last responded before a reinforcer could be obtained. The concurrent schedules were varied across conditions. Discriminability, measured during the symbolic matching-to-sample performance, was high throughout and did not differ across the two procedures. Performance in the concurrent schedules was like that typically obtained using these schedules. Delays were then arranged between completion of the concurrent schedules and presentations of the symbolic matching-to-sample phase. A series of conditions with an intervening delay of 10 s showed that both concurrent-schedule performance and symbolic matching-to-sample performance were affected by the delay in a similar way; that is, choice responding was closer to indifference.

Key words: symbolic matching to sample, concurrent schedules, reinforcer ratio, discriminability, key peck, pigeons

In a concurrent schedule, two or more schedules of reinforcement are simultaneously available and the subject can alternate its responding between them. In a switching-key (or Findley [1958]) concurrent schedule, these two schedules are arranged on one key, but only one schedule is presented at any particular moment. Responding on a second key, the switching key, switches between the two schedules on the main key. Different stimuli are presented to signal which schedule is currently available on the main key.

Typically, subjects allocate a certain portion of their total behavior to each of the two schedules. The generalized matching law (Baum, 1974) provides a description of this behavior allocation as a function of the frequency with which reinforcers are obtained from the two schedules. This relation can be written

$$\left(\frac{B_1}{B_2}\right) = c \left(\frac{R_1}{R_2}\right)^a, \quad (1a)$$

or as its linear logarithmic (base 10) transformation,

$$\log\left(\frac{B_1}{B_2}\right) = a \log\left(\frac{R_1}{R_2}\right) + \log c, \quad (1b)$$

where B denotes number of responses, R denotes number of reinforcers, and the subscripts 1 and 2 denote the two alternatives. The two free parameters, a and c , are determined by fitting Equation 1a or 1b to the obtained data.

The parameter c in Equation 1, known as bias (e.g., Baum, 1974), measures any ratio preference for one alternative over the other that remains invariant across changes in the independent variable (i.e., the ratio of obtained reinforcers, R_1/R_2). Such biases are usually attributed to undetected constant asymmetries in the apparatus or the subject (Baum, 1974). The sensitivity to the reinforcer-ratio parameter, the exponent a in Equation 1, measures the extent to which changes in the independent variable (R_1/R_2) produce changes in the dependent variable (B_1/B_2). For example, when a is less than 1, changes in the reinforcer ratio produce less extreme changes in the behavior ratio. This common result is known as undermatching (e.g., Baum, 1979;

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Taylor & Davison, 1983; Wearden & Burgess, 1982).

Davison and Jenkins (1985) offered an alternative model of concurrent-schedule performance that incorporated the bias parameter, c , but replaced the sensitivity term with a discriminability parameter, d_r . This description of concurrent-schedule performance can be written

$$\frac{B_1}{B_2} = c \left(\frac{d_r R_1 + R_2}{d_r R_2 + R_1} \right), \quad (2)$$

where B , R , c , 1, and 2 are as above, and the parameter d_r measures the discriminability between the two response-reinforcer contingencies in the concurrent schedule. When d_r is 1.00 (i.e., no discriminability between the two response-reinforcer contingencies), the model predicts that the ratio of responding on the two alternatives will always equal the bias parameter, c , irrespective of changes in the reinforcer distribution. As the discriminability between the response-reinforcer contingency increases, d_r approaches infinity. When discriminability is perfect, the performance predicted by Equation 2 is the same as that predicted by the generalized matching law (Equation 1) with an a parameter of 1.00.

Davison and Jenkins (1985) favored Equation 2 over the generalized matching law for a variety of reasons. First, Equation 2 described most existing data equally as well as did the generalized matching law. Only at very extreme reinforcer ratios do the two models make noticeably different predictions. Second, the d_r parameter was conceptually easier to understand than the a parameter of the generalized matching law. Finally, Davison and Jenkins saw the parameter d_r as being closely related to the stimulus discriminability parameter d_s , measured by the Davison and Tustin (1978) behavioral model of signal-detection performance, thus allowing a more parsimonious treatment of performance in both procedures.

The results of Miller, Saunders, and Bourland (1980) and Alsop and Davison (1991) are consistent with a discriminability account of concurrent-schedule performance. These studies arranged various switching-key concurrent schedules that varied the disparity between the two stimuli that signaled which of the two variable-interval (VI) schedules

was available on the main key. The extent to which the reinforcer ratio controlled behavior allocation was an orderly function of the disparity between the stimuli. As stimulus disparity decreased, changes in the reinforcer ratio produced smaller changes in the behavior ratio.

Other researchers have presented similar conceptual or quantitative approaches of concurrent-schedule performance. Both Catania (1966) and Baum (1974) proposed that stimulus control was a determinant of behavior in concurrent schedules. Vaughan and Herrnstein (1987) presented a model virtually identical to Equation 2 to describe the results from a concurrent-schedule experiment in which the availability of the two variable-interval schedules was signaled by the presence or absence of trees in slides. They suggested that the extent of the undermatching in their results was "due to stimulus ambiguity" (Vaughan & Herrnstein, 1987, p. 11).

Burgess and Wearden (1986) presented a model similar to that of Davison and Jenkins (1985) to describe performance on a single VI schedule following the addition of noncontingent reinforcement or differential-reinforcement-of-other-behavior (DRO) schedule of reinforcement. The traditional matching equation for single-schedule performance with such superimposed schedules predicts that any addition of noncontingent reinforcers must decrease the response rate (e.g., Herrnstein, 1970). However, some researchers (Lattal & Boyer, 1980; Lattal & Bryan, 1976; Zeiler, 1979) have found that superimposed fixed-time or variable-time schedules with low rates of reinforcement elevate response rate. Burgess and Wearden suggested that these results occur when the noncontingent food reinforcers (R_2) delivered by the superimposed schedules were not functionally separable from the reinforcers obtained by responding (R_1). In Burgess and Wearden's model the p parameter (similar to d_r in Equation 2) "thus might be interpreted as the degree of 'generalization' from R_2 to R_1 , or the degree of 'confusion' between R_2 and R_1 " (Burgess & Wearden, 1986, p. 79).

The Davison and Jenkins (1985) model, and these related studies, pose an obvious question: How accurately do subjects discriminate between their responses to two concurrent schedules? Past research has shown that subjects can learn similar discriminations. Killeen (1977) trained pigeons to report

whether an environmental change had been contingent upon a response by the subject, or if the change had been noncontingent (produced by a computer). In general, discriminability between these two events was high, but subjects' behavior was consistently biased towards reporting that the change had been contingent.

Lattal (1979) investigated discriminability between a DRO schedule and a DRL (differential reinforcement for low rates of responding) schedule. Completing either schedule led to a choice phase in which one response was reinforced if the DRO had just been completed, and another response was reinforced if the DRL had just been completed. Discriminability between the schedules was high, but not perfect. Furthermore, discriminability decreased when a 3-s delay was arranged between schedule completion and choice-phase presentation, and decreased even further if a 3-s reinforcer was arranged instead of the 3-s delay.

Shimp (1976) trained pigeons to make the same response as that on the immediately prior trial in order to receive reinforcement. The results of this "win-stay, lose-shift" procedure, including the effects of delays and intervening reinforcers, paralleled those of Lattal (1979).

These experiments show that the level of discriminability between the presence or absence of a contingency, or between two different types of contingency, is high but less than perfect. In a concurrent schedule, two operants, often topographically very similar and between which the subject is alternating, lead to the production of a particular reinforcer. Some confusion between the two scheduled contingencies seems likely. Indeed, changeover delays (COD) were first used in concurrent-schedule research to overcome not just simple confusion between the alternatives but to avoid superstitious patterns of responding based on perceived contingencies involving both alternatives (Bruner & Revusky, 1961; Catania & Cutts, 1966).

The present study considered three aspects of discriminability and concurrent-schedule performance. First, the experiments provided an empirical investigation of the discriminability between concurrent response alternatives. In Parts B and C, a switching-key concurrent schedule led to a symbolic matching-to-sample (SMTS) procedure. The subjects identified

to which concurrent alternative they last responded before they received a reinforcer. The concurrent schedules in Parts B and C were varied across conditions. The stimuli used on the main key in this procedure were also used as the sample stimuli in a simple SMTS procedure in Parts A and A_{rep}. This provided an independent measure of the discriminability between these two stimuli when they were not part of a concurrent schedule.

Second, Parts D and E investigated the effects of delaying presentation of the SMTS phase after completion of either of the concurrent schedules. In standard discrete-trial SMTS procedures, increasing the delay between stimulus presentation and the choice phase decreases accuracy for reporting which stimulus was presented (e.g., McCarthy & White, 1987). In the present procedure, however, this delay also further separated the concurrent-schedule responses from the reinforcers, so discriminability between the two response-reinforcer contingencies arranged in the concurrent schedule might show a similar decrease. In other words, the effect of the delay on performance in the SMTS component of the procedure was compared with the effect of the delay on performance in the concurrent-schedule component of the procedure.

Finally, Parts B, C, and E provided sets of conditions for which measures of the discriminability between the concurrent alternatives could be calculated from the concurrent-schedule performance (using Equation 2) and also from the accuracy of responding during the SMTS part of the procedure.

METHOD

Subjects

Six adult former racing pigeons, numbered 171 to 176, were maintained at $85\% \pm 15$ g of their free-feeding body weights. Water and grit were freely available in their home cages, and postsession mixed grain was delivered when necessary to maintain their set weights. All subjects were experimentally naive.

Apparatus

The standard pigeon operant chamber (width 33 cm, depth 31 cm, height 32 cm) contained four response keys 2 cm in diameter, 9.5 cm apart, and 25 cm above the grid floor. These keys were designated A (leftmost key)

Table 1

The sequence of experimental conditions and number of training sessions in each. For conditions that arranged concurrent schedules, the relative frequency of completing the S_1 schedule is shown. For conditions that delayed presentation of the SMTS choice phase, the duration of the delay is given in seconds. The probability of R_w and R_z reinforcers in the SMTS phase is also given. Note the differences in scheduling between Parts A and A_{rep} and Parts B, C, D, and E described in text.

Condition	Relative S_1	Delay	R_w rein- forcer p	R_z rein- forcer p	Ses- sions
Part A					
1	—	—	.500	.500	50
2	—	—	.800	.200	37
3	—	—	.111	.889	37
4	—	—	.889	.111	35
5	—	—	.200	.800	26
Part B					
6	.889	—	.500	.500	31
7	.111	—	.500	.500	28
8	.800	—	.500	.500	28
9	.200	—	.500	.500	38
10	.500	—	.500	.500	25
Part C					
11	.500	—	.111	.889	34
12	.500	—	.889	.111	35
13	.500	—	.200	.800	35
14	.500	—	.800	.200	39
Part D					
15	.300	1.5	.500	.500	33
16	.300	2.5	.500	.500	30
17	.300	4.0	.500	.500	30
18	.300	7.0	.500	.500	37
19	.300	10.0	.500	.500	41
Part E					
20	.700	10.0	.500	.500	51
21	.500	10.0	.500	.500	31
22	.111	10.0	.500	.500	44
23	.889	10.0	.500	.500	65
Part A_{rep}					
24	—	—	.500	.500	36
25	—	—	.889	.111	40
26	—	—	.200	.800	35
27	—	—	.800	.200	46

to D (rightmost key) for convenience. Keys A and D could be transilluminated red, Key B could be transilluminated blue, and Key C could be transilluminated with two intensities of white light (approximately 0.80 cd/m² for S_1 and 2.75 cd/m² for S_2). An effective response on any key required a force of approximately 0.1 N and produced a click. Responses to darkened keys were ineffective

and were not recorded. A reinforcer consisted of 3-s access to a grain hopper situated 10 cm below the midpoint between Keys B and C. During reinforcement, the hopper was illuminated and the keys were darkened. No other sources of illumination were provided. A ventilation fan provided some masking noise. A PDP 8E® computer (later, a PDP 11/73® computer) situated remote from the chamber arranged experimental events and recorded the data using SKED® software (later, SKED® 11).

Procedure

Initial training. All subjects were trained in an autoshaping procedure using a variety of keys and key colors. They were then trained for 34 sessions on single VI schedules, arranged on different keys and key colors in different sessions. When all subjects were reliably responding to lit keys, Condition 1 of Part A began (Table 1). In all parts of the experiment, the daily experimental sessions began in blackout and ended in blackout after either 45 min had elapsed or after 40 reinforcers had been obtained.

Part A. In this discrete-trial SMTS procedure, Key B was dark and inoperative throughout. A trial commenced with one of the two intensities of white light presented on Key C. After a single response on Key C, Key C was extinguished and Keys A and D were lit red. Following a presentation of S_1 on Key C, a peck on Key A produced either a reinforcer or a 3-s blackout, whereas a peck on Key D always produced a 3-s blackout. Following a presentation of S_2 on Key C, a peck on Key A always produced a 3-s blackout, whereas a response on Key D produced either a reinforcer or a 3-s blackout. After the reinforcer or blackout, the next trial started immediately. Reinforced responses were arranged by a single arithmetic VI 30-s schedule. When a VI interval elapsed, the reinforcer was probabilistically assigned either to a Key A response following an S_1 presentation or to a Key D response following an S_2 presentation. Once the reinforcer had been obtained, the next interval started timing. By varying the probability of left-key versus right-key reinforcer assignment, the arranged reinforcer ratio was varied across conditions (Table 1).

At the end of the session, the following

data were recorded: the number of Key A responses and Key D responses following an S_1 presentation, the number of Key A responses and Key D responses following an S_2 presentation, the number of Key A reinforcers, and the number of Key D reinforcers.

Each of these signal-detection conditions continued until all subjects reached a defined stability criterion. After 18 sessions, the last 9 days were divided into three consecutive sets of three sessions. The median point estimates of discriminability and bias (Equations 4 and 5, below) were calculated for each set and bird. If there was no trend across these medians or across the estimates from the last three sessions, performance of that bird was deemed stable. If a trend was present, an additional three sessions were conducted and this process repeated. When all subjects had satisfied the criterion, the condition was changed.

Intermediate training. This was very similar to Part A. However, in Part A a single response extinguished Key C and lit Keys A and D. Now, completion of a single VI schedule on Key C was required before this change took place. This mean interval of the VI schedule was increased from 2 s to 20 s across 20 sessions. When all subjects were reliably responding on Key C, Part B began.

Part B. Figure 1 shows the general procedure. Each trial started with the presentation of a switching-key concurrent schedule. Two arithmetic VI schedules were arranged on Key C. Each schedule was signaled by transilluminating Key C with one of the two intensities of white light. The schedule (and accompanying stimulus) was available on Key C and could be switched by a single response to Key B, which was lit blue. However, unlike a standard concurrent schedule, completion of either VI schedule led to the presentation of an SMTS task. Keys C and B were extinguished and Keys A and D were lit red. If the last response on Key C had been made to the schedule signaled by S_1 , a peck on Key A produced either a reinforcer or a 3-s blackout ($p = .5$), whereas a peck on Key D always produced a 3-s blackout. If the last response on Key C was to the VI schedule signaled by S_2 , a peck on Key A always produced a 3-s blackout, whereas a response on Key D produced either a reinforcer or

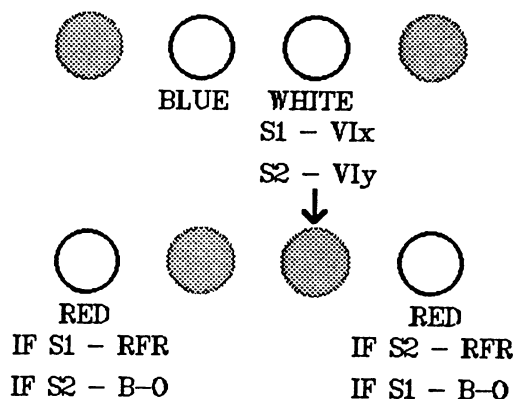


Fig. 1. A diagram of the procedure used in Parts B and C. RFR indicates reinforcement and B-O a blackout.

a 3-s blackout ($p = .5$). Following each reinforcer or blackout, the switching-key concurrent schedule was again presented.

Following each switching response during the concurrent schedule, a 2-s COD prevented responses on Key C from producing the SMTS task or responses on Key B from producing another switch, for a period of 2 s. The concurrent VI schedules ran dependently, in the manner of Stubbs and Pliskoff (1969); that is, a single arithmetic VI 10-s schedule operated, and when an interval had elapsed the next schedule to produce the SMTS task was probabilistically assigned. The timing of the next interval commenced following the end of SMTS reinforcer or blackout. The probability with which SMTS entry was assigned to one or the other concurrent alternative was varied across conditions (Table 1).

At the end of the session, the following data were recorded: The number of responses made on each of the concurrent VI schedules (B_1 and B_2 on Key C), the number of effective switching responses (Key B), the number of Key A responses and Key D responses following a B_1 response, the number of Key A responses and Key D responses following a B_2 response, the number of Key A reinforcers, and the number of Key D reinforcers.

Each condition continued until all subjects reached a defined stability criterion five times, not necessarily consecutively. This criterion was that the median relative total response rate on the S_1 schedule over the last set of

five sessions did not differ from the median over the previous set of five sessions by more than .05.

Part C. In Part C, the arranged probability for entry into the SMTS task was equal for each concurrent schedule (i.e., $p = .5$); in other words, a dependently scheduled concurrent VI 20-s VI 20-s schedule was used throughout. Across conditions of Part C (Table 1), the probability of reinforcement following a correct Key A or a correct Key D response in the SMTS phase was varied. In all other respects, Part C was identical to Part B. Condition 10 of Part B also contributed to Part C (Table 1).

Part D. In Part D, the concurrent schedules were always VI 14 s and VI 33 s for the schedules signaled by S_1 and S_2 , respectively. The probability of reinforcement following a correct Key A response or a correct Key D response was always .5. However, when a response completed either of the two concurrent VI schedules, Keys B and C were extinguished immediately, but the onset of Keys A and D was delayed. In other words, a delayed symbolic matching-to-sample task (DSMTS) was arranged. The duration of this delay was constant within conditions and varied across conditions from 1.5 s in Condition 15 to 10 s in Condition 19 (Table 1). In all other respects, Part D was identical to Parts B and C.

Part E. In Part E, the delay between completion of a VI schedule and presentation of the SMTS task was always 10 s. The probability of reinforcement following a correct Key A response or a correct Key D response was always .5. The ratio of entries into the DSMTS task was varied across conditions by varying the probability with which the two concurrent schedules were assigned a DSMTS entry, as in Part B (Table 1). In all other respects, Part E was identical to Parts B, C, and D. Condition 19 of Part D also contributed to Part E (Table 1).

Part A_{rep} . Part A_{rep} was identical in general procedure to Part A. The reinforcer ratio was varied across four conditions (Table 1).

RESULTS

The summed data across the last seven sessions in each condition were used in the analyses. The various analyses and parts to

the experiment are easier dealt with under separate headings.

SMTS Performance in Parts B and C and Parts A and A_{rep}

For Parts B and C, the SMTS procedure measured the discriminability between the concurrent alternatives. For Parts A and A_{rep} , the SMTS procedure measured the discriminability between the light intensities used in Parts B and C when not incorporated into a switching-key concurrent schedule.

Performance in the SMTS choice phases was analyzed using the Davison and Tustin (1978) behavioral model of signal detection. For a detailed account of these analyses see, for example, Davison and Tustin (1978), McCarthy and Davison (1984), or Davison and McCarthy (1988). In Davison and Tustin's model, performance following an S_1 presentation can be written

$$\log\left(\frac{B_w}{B_x}\right) = a \log\left(\frac{R_w}{R_z}\right) + \log c + \log d_s, \quad (3a)$$

and following an S_2 presentation

$$\log\left(\frac{B_y}{B_z}\right) = a \log\left(\frac{R_w}{R_z}\right) + \log c - \log d_s, \quad (3b)$$

where B_w and B_x are Key A and Key D responses following S_1 , and B_y and B_z are Key A and Key D responses following S_2 . R_w and R_z are the number of reinforcers obtained for correct Key A and Key D responses following either stimulus presentation. The parameters a and c are as in the generalized matching law (see Equation 1b for comparison with Equations 3a and 3b). The parameter d_s measures the discriminability between S_1 and S_2 and is mathematically equivalent to Luce's (1963) choice theory measure of discriminability. This is shown by algebraic subtraction of Equations 3a and 3b, which gives a bias-free measure of discriminability; that is,

$$\frac{1}{2} \log\left(\frac{B_w B_z}{B_x B_y}\right) = \log d_s, \quad (4)$$

where all variables, parameters, and subscripts

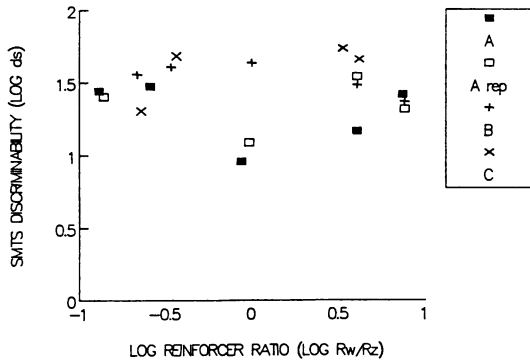


Fig. 2. Estimates of discriminability (Equation 4) plotted as a function of the obtained reinforcer ratio for the mean SMTS data across subjects in Parts A, A_{rep} , B, and C.

are as above. This measure of discriminability is simply the geometric mean of the ratios of correct to incorrect responses following S_1 and S_2 trials. $\log d_s$ may range from 0.0 (no discriminability between the two stimuli) to values approaching infinity (high discriminability).

Equation 4 predicts there will be no systematic variation in discriminability as a function of the reinforcer ratio. Figure 2 plots discriminability ($\log d_s$, Equation 4) as a function of the reinforcer ratio for the mean data across subjects in each condition of Parts A, A_{rep} , B, and C. Across the four parts, there were no systematic variations in discriminability, although the estimates from Parts A and A_{rep} when $\log R_w/R_z$ was close to 0 were unusually low. This pattern, however, was not consistent across individual subjects.

Algebraic addition of Equations 3a and 3b produces a function that predicts that the geometric mean of the left/right response ratios (Key A/Key D) following S_1 and S_2 presentations will be related to the reinforcer ratio in the manner of the generalized matching law (Equation 1b). This bias function can be written

$$\frac{1}{2} \log \left(\frac{B_w B_y}{B_x B_z} \right) = a \log \left(\frac{R_w}{R_z} \right) + \log c, \quad (5)$$

where all variables, parameters, and subscripts are as above.

Figure 3 plots this relation between left/right choice-key responding ($\log[B_w B_y]/[B_x B_z]$) and the reinforcer ratio ($\log R_w/R_z$)

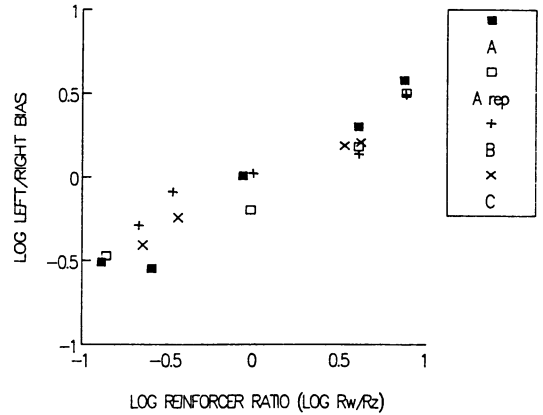


Fig. 3. Estimates of bias (Equation 5) plotted as a function of the obtained reinforcer ratio for the mean SMTS data across subjects in Parts A, A_{rep} , B, and C.

R_z) for the mean data across subjects in each condition of Parts A, A_{rep} , B, and C. Although there are some departures from linearity in Figure 3, these deviations are not consistent across the various parts of the experiment. Furthermore, the effects of changes in the reinforcer ratio ($\log R_w/R_z$) were similar across these four parts of the experiment; that is, the data points lie around similar linear functions.

These analyses using Equations 4 and 5 show that performance during the SMTS procedures was consistent with the predictions of Davison and Tustin's (1978) behavioral model of signal detection. Therefore, a full analysis of the data was performed using Equations 3a and 3b to calculate an overall measure of $\log d_s$ for each subject in each of Parts B, C, A, and A_{rep} . These analyses were conducted using an iterative curve-fitting program. These fits used transformations of these equations into a form using relative response rate and reinforcer rate because in some cases the denominator of a ratio was 0. The parameters and the percentage of variance accounted for by the model (VAC) were obtained by fitting to both Equations 3a and 3b simultaneously, so constraining each to the same parameters for that fit. The results of these analyses are shown in Table 2.

The data were described well by this model. When the data from each subject in each part were analyzed using Equations 3a and 3b, the variance accounted for by the model was greater than 94% (Table 2). Table 2

Table 2

Parameter estimates obtained when the Davison and Tustin (1978) model (Equations 3a and 3b) was used to analyze the data from the SMTS phases of Parts A, A_{rep}, B, C, and E. The percentage of the variance accounted for (VAC) for each analysis is also shown.

Bird	Procedure									
	A	A _{rep}	B	C	E	A	A _{rep}	B	C	E
	$\log d_s$					a value				
171	1.46	1.80	1.56	1.84	0.21	0.34	0.26	0.37	0.09	0.56
172	1.17	0.91	1.43	1.39	0.08	0.37	0.32	0.54	0.58	0.68
173	1.35	3.94	3.45	4.98	0.62	0.25	2.28	0.76	0.00	0.67
174	1.16	1.07	1.34	2.16	0.38	0.41	0.36	0.43	1.45	0.78
175	1.23	1.32	1.89	2.21	0.86	0.60	0.48	0.50	0.49	0.56
176	1.06	4.42	2.27	1.54	0.40	0.49	3.88	1.36	0.00	0.60
	$\log c$					VAC				
171	0.20	0.36	0.12	0.38	-0.03	99.7	99.8	99.9	99.9	97.0
172	-0.30	-0.13	0.08	-0.02	-0.04	98.9	94.5	99.8	99.4	80.6
173	0.17	-0.34	0.88	1.71	0.19	98.8	100.0	100.0	100.0	96.8
174	0.27	0.16	0.07	-0.39	0.26	99.2	99.2	99.7	99.8	99.3
175	-0.09	-0.59	0.06	0.03	-0.18	99.7	99.7	100.0	100.0	94.4
176	0.00	0.57	0.38	-0.27	0.13	98.8	99.3	99.7	100.0	82.4

also shows the estimates of discriminability ($\log d_s$) from the analysis with Equations 3a and 3b. These parameters are plotted in Figure 4 for each subject in Parts A, A_{rep}, B, and C. Discriminability between the sample stimuli, whether they were single presentations of a stimulus (Parts A and A_{rep}) or the concurrent alternatives (Parts B and C), was high. Across Parts A and A_{rep}, there were no systematic changes in $\log d_s$, although Subjects 173 and 176 showed marked increases in $\log d_s$ in Part A_{rep} (Figure 4). The mean $\log d_s$ calculated across all birds for Parts A and A_{rep} was 1.16 and 1.24, respectively.

The estimates of $\log d_s$ obtained from Parts B and C, in which the concurrent schedules led to the signal-detection phase, did not differ significantly across these two parts (Figure 4) except for Bird 173. For Birds 171, 173, 174, and 175, the $\log d_s$ parameter increased; for Birds 172 and 176, $\log d_s$ decreased. Again, the mean $\log d_s$ parameters calculated across all birds were very similar (1.70 and 1.94 for Parts B and C, respectively). Overall, the estimates of $\log d_s$ tended to be greater for Parts B and C than for Parts A and A_{rep}, but these differences were not systematic (e.g., Subjects 171 and 176).

The analysis using Equations 3a and 3b also provided estimates of sensitivity to the reinforcer ratio (a) for each subject in each of the four parts (Table 2). Although there

was considerable variability in the parameter estimates, both across subjects and across the four parts, these differences were not systematic. This is consistent with the earlier analysis of left/right bias shown in Figure 3.

The major findings from these analyses can be simply summarized. There were no systematic differences across subjects between the estimates of stimulus discriminability, $\log d_s$, when the light intensities were simple stimulus presentations (Parts A and A_{rep}) and when the light intensities were associated with the concurrent VI schedules (Parts B and C). Discriminability was very high throughout and, if anything, the estimates of $\log d_s$ were

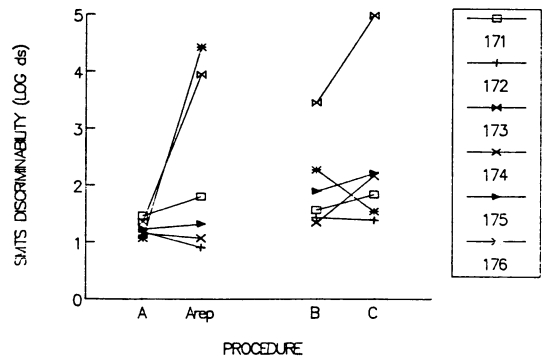


Fig. 4. Estimates of $\log d_s$ (Equations 3a and 3b, Table 2) for each subject in the SMTS phases of Parts A, A_{rep}, B, and C.

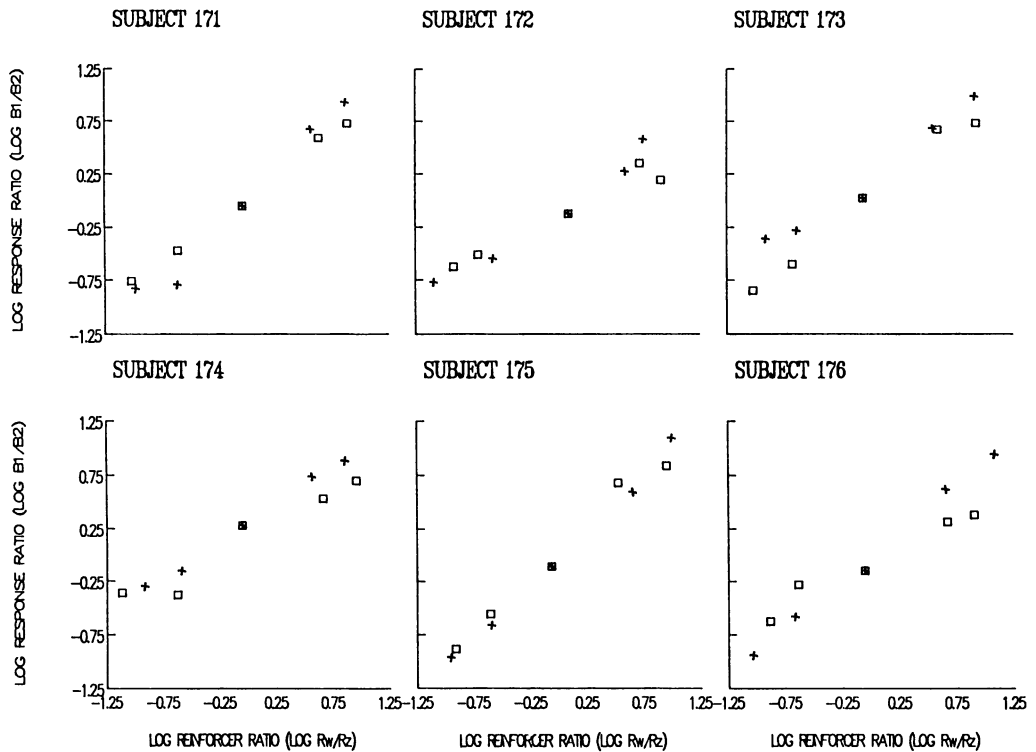


Fig. 5. The logs of concurrent-schedule response ratios plotted as a function of the log obtained reinforcer ratios for each subject in each condition of Part B (pluses) and Part C (squares).

greater in the concurrent-schedule conditions (Table 2, Figure 4) than in the single-stimulus presentations.

Concurrent-Schedule Performance in Parts B and C

Parts B and C arranged a switching-key concurrent schedule on Keys B and C. However, unlike in a standard switching-key concurrent schedule, the subjects had to complete an SMTS task before obtaining a reinforcer. Even with this added component, behavior allocation during the concurrent schedules showed standard concurrent-schedule performance.

In Figure 5, the log response ratios (B_1/B_2) from the concurrent schedules are plotted as a function of the log reinforcer ratios (R_w/R_z) for each subject in Parts B and C. The generalized matching law (Equation 1) and the Davison and Jenkins (1985) model (Equation 2) predict that Figure 5 should show a linear relation. The data show this pattern. Furthermore, there were no systematic differences in performance between Part B, which

varied the obtained reinforcer ratio by varying the concurrent schedules, and Part C, which varied the obtained reinforcer ratio by varying the probability of reinforcement in the SMTS phase.

Table 3 shows the parameters from an analysis of the concurrent-schedule data using the Davison and Jenkins (1985) model (Equation 2). The model accounted for 94% or more of the variance for each subject in each part. Consistent with the data plotted in Figure 5, there were no systematic differences across subjects in the measure of discriminability, d' , across Parts B and C. The estimates of $\log c$ (Equation 2) show no systematic bias for either alternative across subjects (Table 3).

Delays Between the Concurrent-Schedule and the SMTS Phases

Parts D and E introduced delays between the offset of the concurrent schedule, following completion of a VI schedule, and the onset of the SMTS choice keys. Both Parts D and E investigated the effects of these delays on

Table 3

The parameter estimates from the Davison and Jenkins (1985) analysis of the concurrent schedules in Parts B, C, and E (Equation 2). Variance accounted for (VAC) is also shown.

Bird	Procedure		
	B	C	E
log d_i			
171	4.85	1.17	0.59
172	1.00	0.61	0.00
173	0.94	1.48	0.50
174	0.92	0.75	0.43
175	4.76	3.11	1.15
176	1.57	0.62	0.52
log c			
171	0.00	0.01	0.06
172	-0.14	-0.16	-0.17
173	-0.19	0.05	-0.04
174	0.31	0.18	0.06
175	-0.04	0.01	-0.21
176	-0.04	-0.07	0.05
VAC			
171	98.8	99.8	80.4
172	97.7	96.3	0.0
173	97.3	99.4	91.0
174	99.8	94.8	93.0
175	99.8	99.0	83.7
176	99.5	96.2	84.9

both SMTS and concurrent-schedule performance.

Across the conditions in Part D, the delay between the concurrent schedules and the SMTS phase was increased from 0 s to 10 s (Table 1). Figure 6 shows the effect of this delay on discriminability between the concurrent alternatives as measured by the SMTS performance ($\log d_i$, Equation 4). As the delay increased, discriminability eventually decreased for most subjects.

However, there was no corresponding change in the concurrent-schedule performance (Figure 7). Behavior allocation ($\log B_1/B_2$) did not vary systematically as a function of delay. We suspected that this lack of effect might have arisen because the concurrent VI VI schedules were not varied as the delay was increased across conditions in Part D; that is, hysteresis may have contributed to this result. Therefore, in Part E there was always a 10-s delay between concurrent-schedule completion and the SMTS choice key presentation, and the concurrent schedules were varied across conditions.

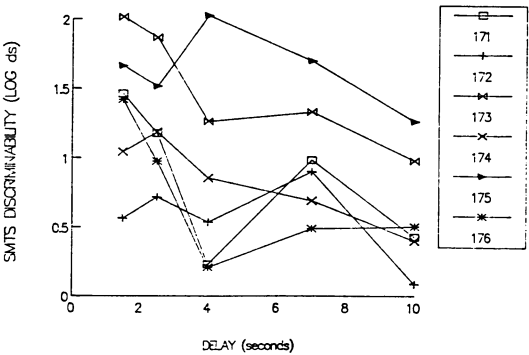


Fig. 6. The estimates of $\log d_i$ (Equation 4) during the SMTS phase are plotted as a function of the delays arranged in Part D for each subject.

The data from Part E were analyzed in the same manner as those from Parts B and C. The SMTS performance was analyzed using the Davison and Tustin (1978) behavioral model of signal detection (Equations 3, 4, and 5). Estimates of discriminability ($\log d_i$, Equation 4) and left/right bias ($\log b$, Equation 5) were calculated for each condition in Part E. Figure 8 shows the group means of these estimates as a function of the obtained ratio of left/right reinforcers. As predicted by the Davison and Tustin model, discriminability ($\log d_i$) did not vary systematically as a function of the reinforcer ratio, and left/right bias ($\log b$) was a linear function of the log reinforcer ratio. This latter bias function was very similar to that obtained from Parts A, A_{rep}, B, and C (Figure 3). A full analysis of SMTS performance in Part E using Equations 3a and 3b was conducted to obtain an overall measure of $\log d_i$ for each subject. Table 2 shows the parameter estimates obtained from this analysis. The VACs were greater than 80% throughout, indicating a reasonably good fit by the model. The SMTS measures of discriminability between the concurrent alternatives ($\log d_i$) for the individual subjects will be presented and discussed below.

Choice ratios are shown in Figure 9. For each subject in each condition, the log ratio of responses during the concurrent schedules ($\log B_1/B_2$) is plotted as a function of the log ratio of obtained reinforcers ($\log R_w/R_z$). Although there was more variability in the data than in the corresponding plot for Parts B and C (Figure 5), there were no systematic

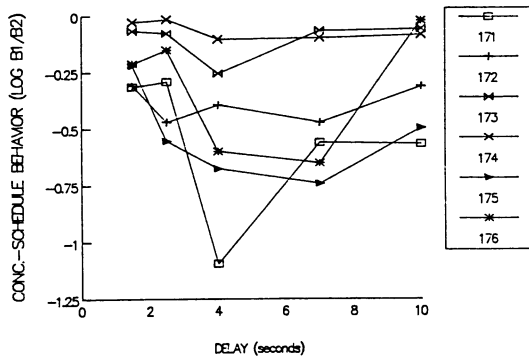


Fig. 7. The response ratios during the concurrent-schedule phase are plotted as a function of the delays arranged in Part D for each subject.

deviations from linearity across subjects. These data were analyzed using the Davison and Jenkins (1985) model of concurrent-schedule performance (Equation 2) and the results are shown in Table 3. The VACs from this analysis were occasionally quite low. However, this probably reflects a decrease in the total variation in the log ratio of responses during the concurrent schedules, especially for Bird 172 (compare Figures 5 and 9). The concurrent-schedule measures of discriminability between the concurrent alternatives ($\log d_c$, Equation 2) for individual subjects are presented and discussed below.

The analyses of the data in Part E using Equations 3a and 3b (Table 2) and Equation 2 (Table 3) showed that the 10-s delay had comparable effects on SMTS choice responding and concurrent-schedule performance. Figure 10 compares the parameter estimates from Part B, which used the same general procedure but without the 10-s delay, and the corresponding measures from Part E. All subjects were less accurate at reporting on which concurrent alternative they last responded during the SMTS phase when the 10-s delay was present; that is, the estimates of $\log d_c$ (Equations 3a and 3b) were lower in Part E than in Part B (Figure 8, Table 2). The 10-s delay had a similar effect on performance during the concurrent schedules. The estimates of $\log d_c$ (Equation 2) were reliably lower for Part E than for Part B (Figure 10, Table 3). Note that Subject 172 showed no systematic changes in concurrent-schedule behavior allocation across Part E (i.e., $\log d_c = 0$), and that for the same subject

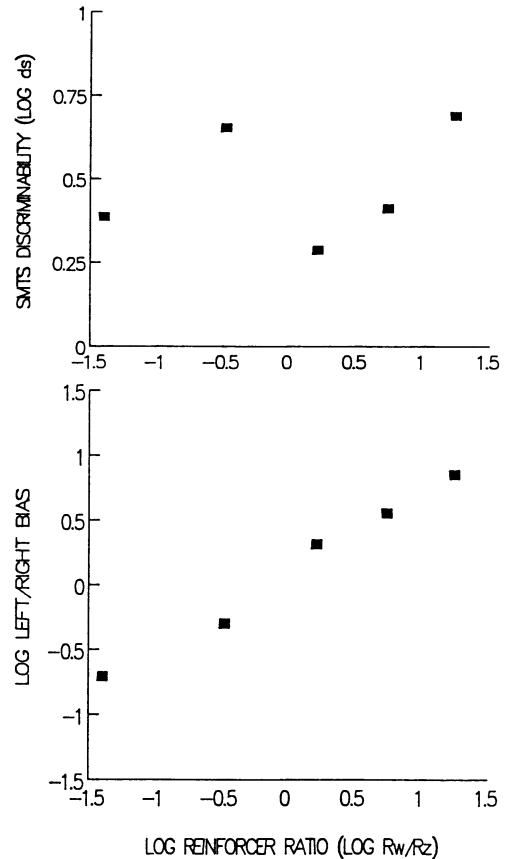


Fig. 8. Estimates of discriminability (Equation 4, top panel) and estimates of bias (Equation 5, bottom panel) plotted as a function of the obtained reinforcer ratio for the mean SMTS data across subjects in Part E.

discriminability between the concurrent schedules measured from the SMTS performance was also very low ($\log d_c = 0.08$).

DISCUSSION

The present study investigated discriminability and concurrent-schedule performance from three perspectives. First, the experiments provided an empirical investigation of discriminability between concurrent response alternatives. For this purpose, a switching-key concurrent schedule led to an SMTS procedure in Parts B and C. The results from these parts of the experiment showed that the subjects were very accurate at this discrimination (Figure 4, Table 2). If anything, the subjects were more accurate when the sample stimuli were the concurrent alter-

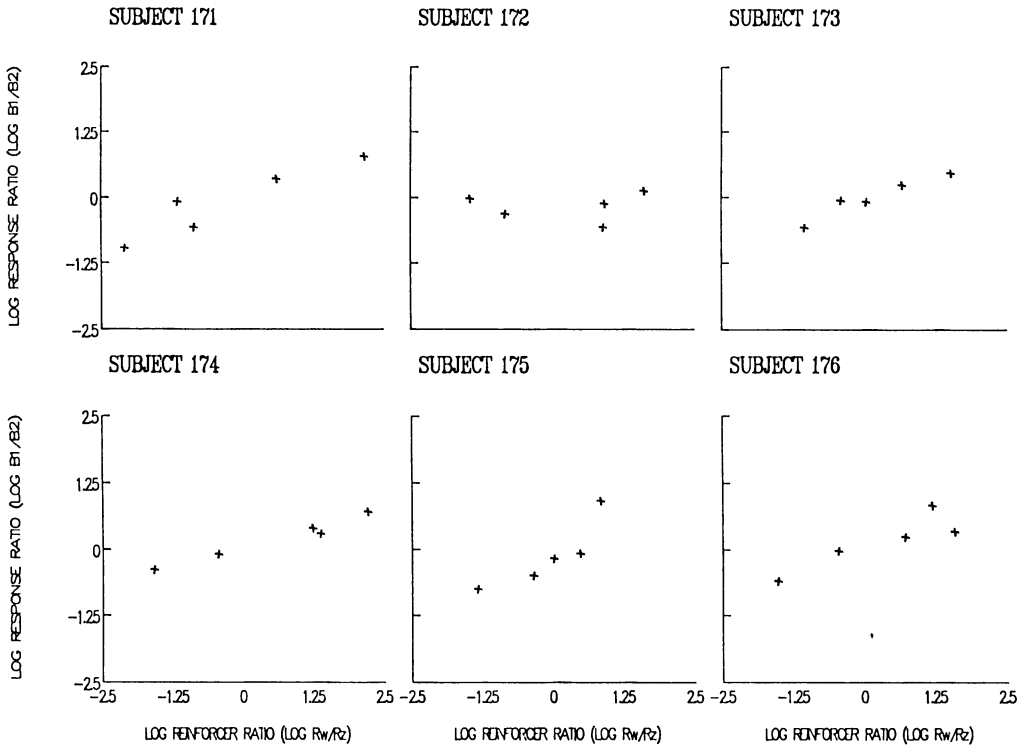


Fig. 9. The logs of concurrent-schedule response ratios plotted as a function of the log obtained reinforcer ratios for each subject in each condition of Part E.

natives than they were when single-stimulus presentations were arranged (i.e., Parts A and A_{rep}). Clearly the topographical similarity between concurrent alternatives and the alternation between them does not produce appreciable confusion.

Second, Parts D and E investigated the effects of delaying presentation of the SMTS phase after completion of either of the concurrent schedules. The results of Part D were informative in an unexpected manner. Part D indicated that delaying the SMTS phase, although decreasing SMTS discriminability between the concurrent alternatives, had no effect on concurrent-schedule performance (Figure 7). However, the results from Part E clearly showed that this was not the case. Behavior allocation during the concurrent schedules was less extreme with a 10-s delay than in corresponding conditions with no delay (Figures 9 and 10). This result suggests that hysteresis can play an important role in procedures of this type. Measuring behavior in one constant part of a procedure while another part is gradually changed can lead to misleading results.

The change in concurrent-schedule performance observed with the 10-s delay in Part E (i.e., the decrease in $\log d_r$) was interesting in its own right. This effect may offer new perspectives on some problems in the study of choice. For example, the effects of delayed reinforcement on choice have typically focused on the value of the reinforcer changing with delay (e.g., Mazur, 1984). Delaying reinforcers may decrease the value of the reinforcer, but it may also decrease the discriminability between the concurrent alternatives leading to that reinforcer. Indeed, the hyperbolic decay model of Mazur (1984), describing the effects of delay on the value of reinforcers in choice procedures, and the hyperbolic decay model of Harnett, McCarthy, and Davison (1984), describing the effects of delayed stimulus control in short-term memory experiments, are algebraically very similar. The results of Part E suggest that these two models may be simply capturing the same effect.

On the other hand, one could argue that the change in concurrent-schedule performance during Part E was a function of the

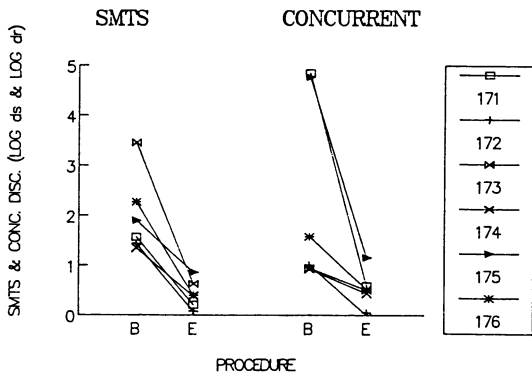


Fig. 10. For each subject in Parts B and E, the SMTS estimates of $\log d_s$ (Equations 3a and 3b, Table 2) and the concurrent-schedule estimates of $\log d_s$ (Equation 2, Table 3).

delayed reinforcers per se and was unrelated to the change in discriminability found in the SMTS choice phase (i.e., the decrease in $\log d_s$). However, it is conceptually neater and more parsimonious to consider both as a function of the same process, that is, as a decrease in the discriminability between the concurrent alternatives.

Third, the present experiment investigated the viability of the Davison and Jenkins (1985) model of concurrent-schedule performance (Equation 2). Here, the results were mixed. There was some support for the use of the d_s parameter (Equation 2) in the analysis of concurrent-schedule performance (Davison & Jenkins, 1985). Although estimates of $\log d_s$ were high throughout, the subjects did make mistakes in the SMTS phases of Parts B and C. Incorrect discriminations would predict the systematic undermatching commonly found in concurrent schedules. On the other hand, accuracy during the SMTS phase of Parts B and C was too high; that is, more errors in discrimination would be necessary to produce the degree of undermatching typically found in concurrent schedules. Perhaps this discrepancy arises from other sources. For example, receiving the reinforcer may itself impair discriminability of the response-reinforcer contingencies in concurrent schedules. Lattal (1979), Shimp (1976), and Killeen and Smith (1984) showed that discriminability was far lower if stimulus presentation and the choice phase of the SMTS were separated by a reinforcer than if they were separated by a period of blackout of similar duration.

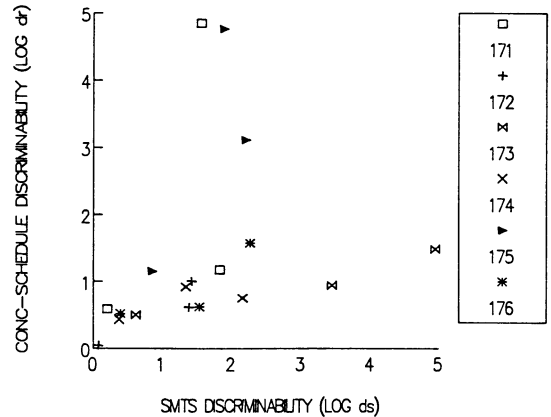


Fig. 11. For each subject in Parts B, C, and E, the concurrent-schedule estimates of $\log d_s$ (Equation 2, Table 3) are plotted as a function of the corresponding SMTS estimates of $\log d_s$ (Equations 3a and 3b, Table 2).

Killeen and Smith actually suggested that reinforcement might "erase" memory in some manner. However, extending such an explanation to the present experiment at this point seems highly speculative at best.

Davison and Jenkins' (1985) model can also be assessed by comparing concurrent-schedule performance ($\log d_s$, Equation 2) and SMTS performance ($\log d_s$) within and across Parts B, C, and E. The 10-s delay in Part E produced similar decreases for both parameters (Figure 8); there was also some consistency in the extent of this effect within subjects. For example, Bird 175 was the most accurate throughout the SMTS phase of Part E ($\log d_s = 0.86$) and this subject's concurrent-schedule performance was also most sensitive to changes in the reinforcer ratios (in fact, the $\log d_s$ for Bird 175 in Part E, 1.15, was greater than the $\log d_s$ for some subjects in Part B). Bird 172 performed poorly during the SMTS phase of Part E ($\log d_s = 0.08$) and also showed no systematic changes in concurrent-schedule behavior across conditions ($\log d_s = 0$). These consistencies suggest that $\log d_s$ measured in the concurrent-schedule phase and $\log d_s$ measured in the signal-detection phase are related.

Despite these consistencies, a more complete comparison of the SMTS $\log d_s$ and the concurrent-schedule $\log d_s$ does not provide convincing support for the Davison and Jenkins (1985) model. Figure 11 shows the relation between the corresponding estimates of these two parameters obtained from Parts B, C,

and E for each subject. Although there is an obvious correlation between the two measures, one would expect a much closer relation if they were effectively capturing the same effect.

How do the results of the present experiment contribute to the issue of discriminability in concurrent schedules and to models describing this effect? At the general level, the idea that behavior allocation in concurrent schedules is affected by the discriminability between the concurrent alternatives remains viable. Previous experiments (Alsop & Davison, 1991; Miller et al., 1980; Vaughan & Herrnstein, 1987) have shown this effect quite convincingly, and the results from Part E of the present experiment are also consistent with this approach by showing greater undermatching under conditions that reduced the discriminability of the concurrent schedules (d_s). However, the modeling of such effects and the interpretation of the parameters used in such models obviously need further work. For example, the present experiment focused on the physical disparity between the concurrent alternatives, but behavior allocation in concurrent schedules may depend on other factors as well. The scaling of the difference between the rates of reinforcement obtained from the two alternatives is one obvious candidate. Indeed, Baum (1974) compared the parameter a of the generalized matching law (Equations 1a and 1b) to traditional psychophysical scaling exponents. Perhaps some of the discrepancies between SMTS $\log d_s$ and concurrent-schedule $\log d_s$ arise because the latter measure must accommodate both differences in reinforcer rate and differences between the physical disparity of the concurrent alternatives. As Vaughan and Herrnstein (1987) noted, undermatching may be the standard result of concurrent-schedule responding even if the concurrent alternatives are perfectly discriminable.

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